THE DISTRIBUTION AND STRATIGRAPHY OF PERIGLACIAL FEATURES IN UTOPIA PLANITA, MARS.

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Introduction: We suggest the periglacial landforms identified in Utopia Planitia by numerous workers (e.g., Costard and Kargel, 1995; Lefort et al., 2008; Soare et al., 2008) represent a complex arrangement of multiple discrete periglacial units rather than just superficial surface modifications of existing geological units. Previously undefined periglacial units can be identified through the observation of the various geomorphologic landforms (including polygons, scalloped depressions and gullies) present on the surface and their spatial relationships to one another. The nature and origin of the ice-rich substrate (or mantle) in Utopia Planitia is believed to be the result of periodic atmospheric deposition of an ice and dust mixture driven by changes in Mars' obliquity. Although this ice-rich substrate is usually referred to as a single unit, it has been proposed that multiple distinct layers of this substrate are present in the area. We suggest that there is evidence from the periglacial landform distribution trends investigated here to support the related idea of multiple episodes of periglacial activity represented by separate units in Utopia Planitia. These landforms vary in size and morphology throughout the region and we suggest units representing multiple episodes of periglacial activity can explain morphological differences as well as the discrepancies between areas where, for example, scalloped depressions appear to post-date gullies and other areas where they pre-date gully formation. This study focuses on the largest periglacial unit identified in the area and aims to introduce a clearer understanding of the large-scale geographical context of the multiple episodes of periglacial activity in Utopia Planitia.

Periglacial Landforms as Climate Indicators: The intricate valley networks, deltaic systems and fluvial channels that span vast areas of Mars are geomorphologic fossils, remnants of a time marked by a warm, wet and dynamic environment, a time in the ancient past when Mars was not the cold desert we see today (Baker, 2001). Mars has experienced many changes in its environment over the course of its lifetime and as we do with Earth work has begun to reconstruct these past environments and understand how the climate has shifted so dramatically. Recently geological evidence has been mounting for a period of dynamic climate change on Mars during the last 100 million years. Layered deposits in the Polar Regions (Herkenhoff and Plaut, 2000) equatorial mountain glaciers (Fastook et al., 2008) and young glacial and periglacial landforms in the mid-latitudes all tell us something about the movement of water and carbon dioxide between the subsurface and atmosphere (Jakosky and Phillips, 2001). These ground observations coupled with climate models based on orbital fluctuations all point to a changing climate in Mars' recent past.

This study focuses on the periglacial landforms of Utopia Planitia and how their distribution and stratigraphy can help in building the history of recent climate change on Mars. Periglacial landforms were first identified on Mars in images sent back by the Mariner spacecrafts in the 1970's. Networks of patterned ground and areas of degradation likened to thermokarst on Earth peaked interest in the study of periglacial activity on Mars, particularly in the Northern Plains where these landforms are common.

The significance of periglacial landforms lies in their diagnostic value as environmental indicators, both on regional and localized scales. The occurrence and morphology of periglacial landforms are determined by a complex combination of geologic and climatic conditions. As such the study of an ancient periglacial landscape is useful in reconstructing the past environmental conditions at the time of formation. Also, its preservation and/or level of degradation can tell us something about the environmental change in the intervening time. It must be noted however that in doing this assumptions are made on the process-form relationship between the environmental conditions and the landforms, assumptions that are perhaps a 'best guess' scenario but whose validity can also be strengthened on the basis of additional evidence in this case from, for example, climate models and Earth analogue studies.

At its simplest level the presence of periglacial landforms indicates the presence of frozen ground which in turn points to a cold climate. Usually this also indicates the presence of water in its solid state but some periglacial landforms can form in a dry environment. The difficulty lies in understanding what environmental conditions are manifested in specific landforms. The chain leading from environmental conditions to physical and chemical processes to morphology of the landform has variations too numerous for easy understanding and elements whose effects may be too subtle can have their importance overlooked. The presence of specific periglacial landforms is likely an indicator of the smaller scale, localized conditions for example, the physical and chemical nature of the material they form in, topography, and hydrological variations (Karte, 1983). The size of periglacial landforms also can be related to their stage of growth or their response time to environmental changes. Small landforms therefore may be valuable in that they may represent a simpler system of cause and effect where their formation and growth may be linked more directly to specific changes in environmental conditions. The narrower the range of environmental conditions needed to form a specific landform the higher the diagnostic value of that landform. The trick is obviously defining the range for a specific landform in the first instance, a difficult feat given the complex nature of the environment-process-form relationship, but a feat made easier when aimed at simpler forms dependent on fewer processes and conditions.

Often the study of periglacial landscapes tends towards the descriptive rather than analytical meaning the diagnostic association between climate and specific form has not been extensively studied other than the general association between a periglacial landscape and a cold climate. Field experiments on periglacial sites are obviously limited to small localized scales. On these small scales the influence of non-climatic factors are often much stronger than the influence of the larger scale regional climatic conditions. In this paper we have focused on a large scale study of the periglacial landscape in Utopia Planitia in northern Mars. We will show how mapping the distribution of periglacial landforms and understanding how different phases of periglacial activity are represented stratigraphically can contribute to the reconstruction of past environments and climate change on Mars.

Utopia Planitia: Utopia Planitia is one of the Great Northern Plains of Mars centred at 49.7°North and 118.0°East with a diameter of approximately 3300 kilometers. A roughly circular basin, it is thought to be the result of a major impact early in Mars' history (McGill, 1989). During the Hesperian and into the Amazonian periods, Utopia has undergone modification from tectonic and volcanic activity. Volcanic material and flows can be seen in the east of the region towards the Elysium Province. Recently the basin has been a major depocentre resulting in its gentle slope from rim to centre. This infilling material is an ice and dust mixture thought to be the result of periodic atmospheric deposition driven by changes in Mars' obliquity.

Using periglacial environments in the study of past climates differs somewhat between Earth and Mars. On Earth periglacial landforms are somewhat transient, some being erased almost as quickly as they form. On Mars however a less dynamic cycle of formation and erosion has allowed the preservation of these landforms. As higher resolution imagery has become available this landscape has been studied in greater detail with the landform assemblages being recognised as analogous to permafrost and periglacial landscapes on Earth. The ubiquity of periglacial landforms in Utopia Planitia and the somewhat limited availability of other environmental indicators is why periglacial investigations have come to the forefront of climate research.

Methodology: We have carried out an extensive survey of periglacial-like landforms in Utopia Planitia. The area investigated stretches across Utopia from approximately 20 to 60°North and 70 to 140°East. Thermal Emission Imaging System (THEMIS), Mars Orbiter Camera (MOC) and Mars Reconnaissance Orbiter Context Camera (CTX) images for this area were examined. With hundreds of images analysed, this represents the most detailed study of this area to date. High Resolution Imaging Science Experiment (HiRISE) images were also studied to facilitate distinguishing between certain landforms. Figure 1 shows the distribution of scalloped depressions and small-scale polygons identified from these images over a morphometric map of the region (Capitan, 2012). Also noted was whether a feature was in or associated with a crater or in the surrounding flat terrain.

Distribution of Periglacial Features: With the observation and mapping of these periglacial landforms some trends in their distribution emerge. There is a distinct band of scalloped depressions which stretches across the extent of the study area. This includes individual scalloped depressions as well as more degraded areas where depressions have coalesced. In addition, in this area are small-scale polygons although they are also found in areas outside of the boundary on the map where scalloped depressions are not found. Also of interest is the spatial separation of gullies and scalloped depressions in Utopia Planitia, an anomaly not previously noted in this debate.

Defining a new Periglacial Unit(s): The presence of periglacial landforms on Earth is indicative of an ice-rich substrate (French, 2007) and the same is thought to be true on Mars. In Utopia Planitia this substrate is of varying thickness, possibly up to many hundreds of meters (Madeleine, 2009). The nature and origin of this ice-rich substrate (or mantle) is still a matter of debate but the commonly held theory is that it is the result of periodic atmospheric deposition of an ice and dust mixture driven by changes in Mars' obliquity (Head, 2003). It has been suggested however that these periglacial landforms are not present in this ice-rich substrate but are in a unit underlying it (Soare, 2011). This was concluded through the observation of scalloped depressions with possible mantle deposits on their floors. Alternatively, it may be that rather than the scalloped depressions being filled in with mantle deposits, they have extended down through their unit to expose an underlying, older unit of ice-rich mantle material which in turn suggests that the material the depression is in is different than the mantle under it because otherwise the depression would continue to extend. Although this ice-rich substrate is usually (albeit not always explicitly) referred to as a single unit it has been proposed that multiple distinct layers of this substrate are present in the area (Head, 2011). We suggest that there is evidence from the periglacial landform distribution trends investigated here to support the related idea of multiple episodes of periglacial activity represented by separate units in Utopia Planitia.

Extent and stratigraphic relations of the Periglacial Unit: This study has defined the boundaries of the large periglacial unit for the first time (Fig. 1). The unit covers an area of approximately 1,150,000 km2. It overlies the Elysium Flows on its eastern extent and the Glacial Unit to the west (see (Osinski, 2012) for details of this glacial unit). To the north and south the unit dissipates gradually and as such the boundaries here are difficult to accurately determine. Combining the visual datasets with altimetry data, however, has allowed these boundaries to be better estimated than with visual information alone (Capitan, 2012). Figure 2 shows an area along the contact between the periglacial and Elysium units. The lower albedo material is part of the periglacial unit and small ‘islands’ of this material is seen within the higher albedo Elysium unit. We suggest that at this farthest eastern extent of the Periglacial Unit it is quite thin and has degraded variably to expose the underlying Elysium unit. Figure 3 shows a section of the contact between the Periglacial Unit and the Glacial Unit to the west. This clear divide between the Periglacial on the right of the image and the Glacial on the left can be followed quite readily due to the high density of CTX images in this area.

Discussion: Rather than polygon terrain and scalloped depressions being thought of as periglacial modifications to pre-existing non periglacial units (e.g., Vastitas Borealis Formation), we propose here that they are landforms diagnostic of distinct and previously undefined periglacial units. These landforms vary in size and morphology throughout the region and we suggest units representing multiple episodes of periglacial activity can explain morphological differences as well as the discrepancies between areas where, for example, scalloped depressions appear to post-date gullies and other areas where they pre-date gully formation.

Concluding that all instances of periglacial geomorphology are representative of a single occur -rence of periglacial activity is to underestimate the vastness of Utopia Planitia both spatially and temporally. It is worth remembering that the area surveyed spans almost 6,500,000 km2, an area 6 times the size of the Canadian High Arctic where a complex geologic and climatic history is recorded in the stratigraphic relationships between numerous distinct units.

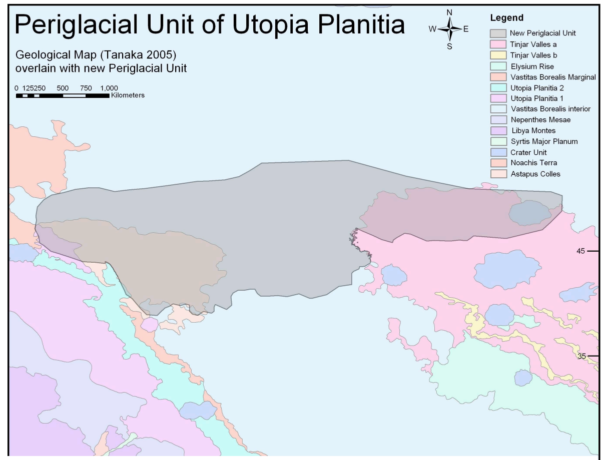

Figure 1. *Map of Utopia Planitia showing the extent of the previously undefined Periglacial Unit over a geologic map of the area (Tanaka et al, 2005).*

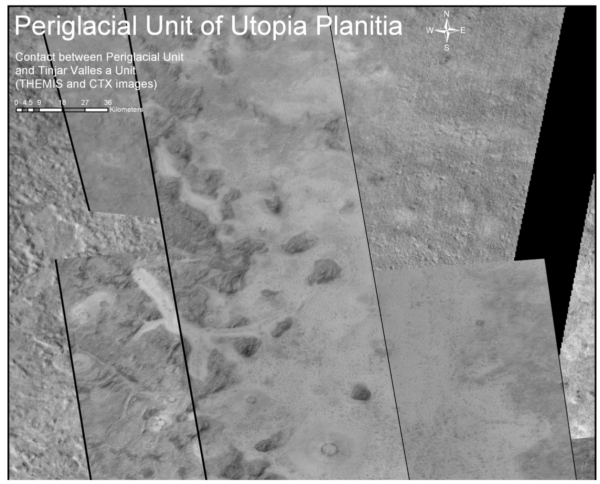

Figure 2. *CTX mosaic, centred on image B17_016442_2252_XI_45N257W showing contact between Periglacial Unit (low albedo) and Elysium Flows (high albedo).*

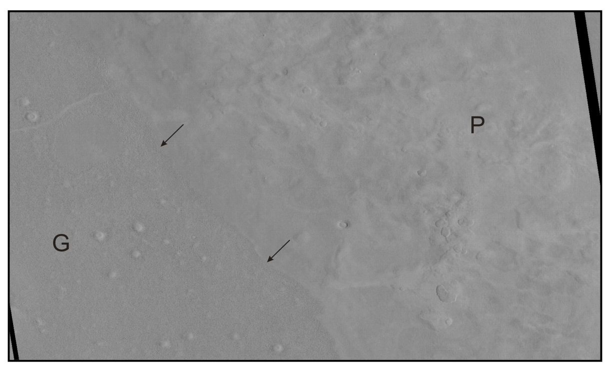

Figure 3. *CTX image B 19_016944_2254_XI_45N282W showing contact between Periglacial Unit (P) and Glacial Unit (G)*

This study has shown that by using observations of the landforms present on the surface of Western Utopia Planitia and investigating how they relate to each other a clearer understanding of the area as a whole and the history of its landscape can be attained. While geological mapping of Utopia Planitia will always be somewhat limited when confined to imagery and satellite data, the high resolution imagery and the increasing coverage of the region now available is allowing a start to be made on constructing the most detailed stratigraphical history of Utopia Planitia to date.

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